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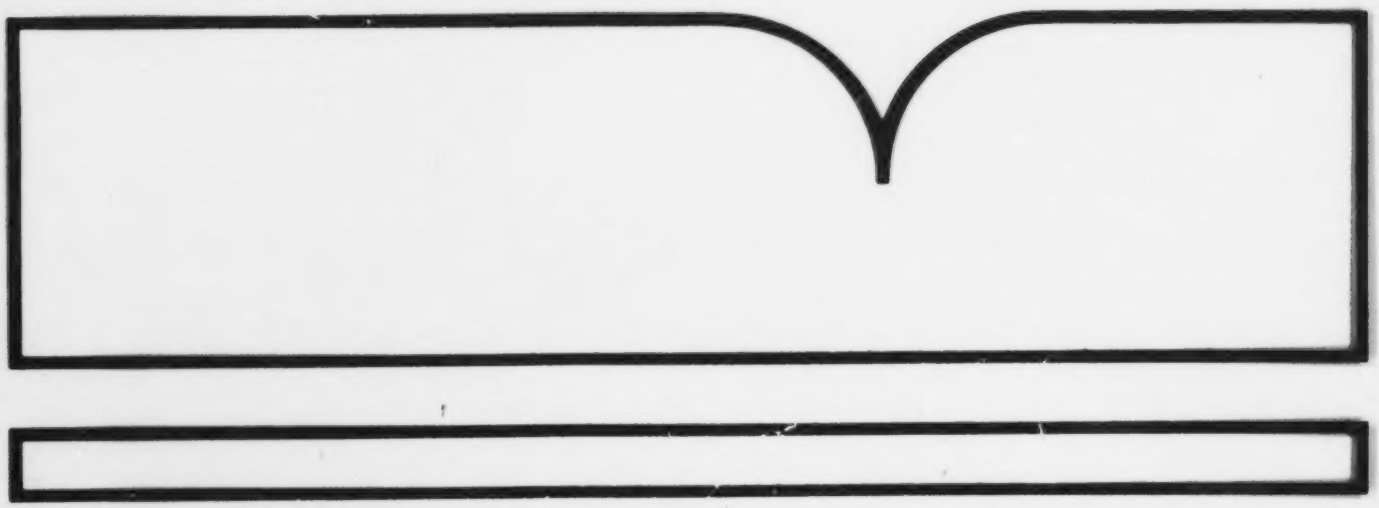

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HYDROLOGIC SIMULATION PROGRAM - FORTRAN: DEVELOPMENT, MAINTENANCE AND APPLICATIONS

by

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ABSTRACT

Nonpoint sources are significant contributors of pollutants to receiving waters and quantification of their impact is a difficult task. Evaluation of these pollutants requires a tool capable of simulating the hydrologic cycle in a river basin. The Hydrologic Simulation Program - FORTRAN (HSPF) is designed to meet this need. This paper examines the development of HSPF from two perspectives -- the research involved in developing its simulation algorithms and the software concepts used in implementing these algorithms. As HSPF was a major software development project, perhaps the first in water resources modeling to use structured programming, the experience with maintenance and support of the program is discussed in detail. Two applications in urban hydrology and water quality assessment are discussed, as well as future directions for the computer program.

Keywords: hydrology, simulation, nonpoint sources, structured programming, water quality

INTRODUCTION

Nonpoint sources are significant contributors of pollutants to streams and lakes and quantification of their impact is a difficult task. Among these pollutants are sediment, pesticides, nutrients, oxygen demanding substances, and toxicants. The hydrologic cycle is the primary force moving pollutants to and through aquatic systems. A comprehensive evaluation of these pollutants thus requires a tool capable of simulating the hydrologic cycle in a river basin system. The Hydrologic Simulation Program - FORTRAN (HSPF) (Johanson, Imhoff and Davis, 1980; Johanson et al., 1984) is designed to meet this need.

HSPF uses such information as the time history of rainfall and temperature and such characteristics of the land surface as type of cover, soil properties, and management practice to simulate the quantity and quality of runoff. Water, sediment and pollutant mass flux are predicted. This information is used, along with characteristics of the stream channel and bed, to simulate fate and transport of pollutants in streams. An assessment procedure for pollutant effects is included. To manage time series data, HSPF includes a data base management system to process the potentially large amount of input data and typically larger amount of simulation output. Routines are provided to analyze and present the data for ease of interpretation.

MODEL DEVELOPMENT AND TESTING

The concept of a simulation model with HSPF's scope evolved from a need identified in the late 1960's by the U S EPA to simulate pesticide fate and transport on the land surface. A research program was begun to develop sediment and pesticide algorithms compatible with the Stanford Watershed Model and to collect a data base for model testing. Concern with enrichment of lakes and reservoirs in the early 1970's prompted the addition of nutrients to the program. This research program led to the development of the Agricultural Runoff Management (ARM) Model (Donigian et al., 1977). A similar concern with urban nonpoint sources prompted the development of an urban counterpart -- the Nonpoint Source (NPS) Model (Donigian and Crawford, 1976). The major difference between that model and its contemporary urban models was the NPS model's capability for continuous simulation and more detailed snowmelt and sediment transport algorithms.

Although simulation of nonpoint loads is helpful for evaluating the impact of management alternatives, the efficacy of these practices must be evaluated on the basis of instream effects. Thus the HSPF project was conceived to link loading and instream models. Many of the concepts incorporated in the design of HSPF came from experience gained with the Hydrocomp Simulation Program (HSP) (Hydrocomp, 1969). The effectiveness of an integral data base management system for time series information had been proven in HSP. Moreover, the instream fate and transport algorithms for water, sediment and pollutants in HSPF are a combination of HSP's routing and water quality algorithms and sediment transport and pesticide fate algorithms from the Sediment - Radionuclide Transport (SERATRA) model (Onishi et al., 1979) and the Exposure Analysis Modeling System (EXAMS) (Burns et al., 1982). In HSPF, a frequency analysis (Olsen and Wise, 1979) links time-varying pollutant concentrations with toxicologic data for risk assessments.

In conjunction with model development, a complimentary data collection program for model testing was undertaken (Barnwell and Johanson, 1981). Data, primarily for testing nutrient and pesticide algorithms, have been collected in the Georgia Piedmont, northern Michigan, northwestern Ohio, coastal North Carolina, and east-central Iowa. Testing of the urban component was done largely on existing data bases in North Carolina, Wisconsin and northern Virginia. More recently, the ARM and HSPF agricultural runoff algorithms have been evaluated in an extensive testing program using these data bases and others collected by the U S Department of Agriculture (Schaefer et al., 1982; Lorber and Mulkey, 1981).

The integrated runoff/instream organic chemical fate and transport algorithms have been extensively exercised on the Iowa data base in an EPA-sponsored project (Donigian et al., 1983) and independently in Nebraska on data collected in the Dee Creek Watershed (Gilbert et al., 1982). These algorithms have also been compared with other instream models (Mulkey et al., 1982). These studies have concluded that HSPF is an applicable and generally useful tool for evaluation of these types of chemical contaminants. The pesticides simulated have properties similar to many organic chemicals of concern in that they exhibit a significant affinity for sediment.

SOFTWARE DESIGN

At the outset of the HSPF project, it was clear that integration of the existing computer programs would be a massive undertaking. Rather than "patching" existing models together, it was decided to redesign HSPF as a new, integrated system using the concepts of structured programming (IBM, 1974). The representation of physical processes used in predecessor models would be preserved to maintain consistency but the resulting code would be new. The new system was also designed to easily incorporate additional capability and was geared to implementation on minicomputers. The entire system conforms to the 1966 ANSI FORTRAN IV standard with two extensions -- direct access input/output and enclosure of literals in single quotes (Johanson, Imhoff and Davis, 1980).

The resulting design incorporated three new simulation modules and six utility modules. The three simulation modules are:

> PERLND - Largely consisting of algorithms from the ARM and NPS models, this module is designed to simulate a pervious land segment (hence, the acronym PERLND). It simulates the water balance including snowmelt, erosion as a function of rainfall intensity and overland flow rate, agricultural chemicals using detailed process descriptions, or other pollutants using empirical sediment-pollutant relationships.
>
> IMPLND - Designed to simulate impervious land segments, the water balance is like PERLND except that no infiltration occurs. Pollutant algorithms are similar to urban models such as the Storm Water Management Model (Huber et al., 1981).

RCHRES - Designed to simulate river reaches or completely mixed lakes, water routing uses the kinematic wave approximation. Sediment transport, including deposition and erosion, uses either the Colby or Toffaleti method for the sand fraction and the critical shear stress concept for silts and clays. Temperature is modeled using an energy balance and nonconservative contaminants may be modeled with either a simple first-order approximation or second-order kinetic expressions developed for organic chemicals. Oxygen and nutrient cycling include BOD; nitrogen, phosphorus and carbon; and three types of plankton -- suspended algae, attached algae and zooplankton.

Utility modules are designed to give the user maximum flexibility in manipulating simulation input and output. Current modules include:

COPY - This module copies time series both internally and from specially formatted external files.

PLTGEN - Designed to interface with a stand-alone plot program or as input to another simulation or data analysis program, this module outputs a specially formatted sequential file.

MUTSIN - The mirror image of PLTGEN, this module provides an alternate input format and is designed to accept input from other simulation programs.

DISPLY - This module provides a neatly formatted universal output table.

GENER - This module provides time series transformation and combination functions useful for simple calculations.

DURANL - Time series data are subjected to a duration and excursion analysis and elementary statistics are computed. Potential lethality of chemicals can be evaluated.

PROGRAMMING

Software development followed a rigid design standard. Developing, modifying, or understanding a large computer program can be frustrating unless a consistent design is followed. Computer scientists have identified program structure as a prime consideration in large development projects. One design philosophy that formalizes this process is structured programming (IBM, 1974). Structure charts are a valuable tool in this process and HSPF's developers made extensive use of them. The structure charts for HSPF cover 80 pages in the documentation and provide a visual table of contents for the program.

The development of structure charts preceded writing of the "pseudo-code," an English-like noncompilable language describing program logic. The pseudo-code was translated into FORTRAN using the five "structures" that are a fundamental tenet of structured programming - SEQUENCE, IFTHENELSE, WHILEDO, DOUNTIL, and CASE. FORTRAN 77 now makes implementation of these structures substantially easier.

The arrangement of variables in a large program is second in importance only to the code itself. In HSPF, variable arrangement is structured and documented using a technique similar to structure charts called Operation Status Vectors (OSV). OSVs are used to document the structure of data both in memory and on disk.

HSPF uses several disk-based files including the Time Series Store (TSS) -- the primary repository for simulation input and output; instruction files that are created from the user's input and that govern its operation in the simulation loop; and the self-documenting information, error message and warning message files. Maximizing use of disk-based files for textual information makes for more efficient use of machine memory. Use of such files also will facilitate translation of applications to languages other than English.

The User's Control Input (UCI) is structured as well and follows a logically consistent format. The UCI begins with the GLOBAL block that contains information applying to an entire run. The time step and sequence of operations (individual application or utility module) are specified in an OPN SEQUENCE block. The information pertinent to a particular operation (e.g., PERLND) is grouped into control flags, general information, model parameters and initial conditions for state variables. An especially convenient feature allows free use of blank lines and a comment line may be entered by placing "****" anywhere on it. As it scans the UCI, HSPF's Run Interpreter will ignore redundant information and will check user-supplied values against valid values contained in the information file. Default values are supplied for omitted information if appropriate. Either English or metric units may be specified for input and, independently, for output.

HSPF produces two kinds of output -- printed and time series. Printed output includes the Run Interpreter scan of the UCI and regular summaries of simulation output. Time series output consists of fluxes and state variables at user-selected intervals ranging from 1 minute to 1 year. This output may take tabular form, be plotted, or be stored on disk in the TSS.

MAINTENANCE

Initial development and testing of HSPF was completed in early 1980. The initial release of the code was operational on Hewlett Packard 3000 and IBM 370 computers. Since that release, the program has been made operational on Control Data Corporation, Digital Equipment Corporation, Harris, Univac, Burroughs, Prime and Data General computers. In order to support HSPF users, EPA initiated a continuing maintenance and support program involving four major tasks: distribution of the code and documentation, maintenance of the code and documentation, user support and error correction, and modifications and enhancements.

Distribution of code and documentation is through the Center for Water Quality Modeling at the EPA's Environmental Research Laboratory in Athens, GA (Barnwell, 1984). An IBM-compatible magnetic tape is available on loan to anyone. Either machine-specific tapes or conversion notes for other systems are available. Through December 1983, 93 copies of the latest release (Version 7) had been distributed.

Maintenance and user support activities are performed under contract. The contractor maintains the master copy of the code and documentation and updates it as appropriate. The master copy is stored as a library of subroutines and common block parts and a merge program is used to generate a new release. The master documentation (except for figures) is also kept in computer compatible form.

User support and error correction activities have been centralized at a single point. User reports of errors are evaluated to determine whether the problem is a result of user misunderstanding of the documentation (classified as a "user problem") or a problem requiring a work-around (classified as a "minor problem") or a code correction (a "major problem"). To date, user problems have averaged less than 1/month. Minor problems have occurred with a frequency of 1.25/month and major problem frequency has averaged just over 1/month. Only 25 problems requiring code changes have been reported in the HSPF system that consists of nearly 75,000 lines of FORTRAN code.

Additional user support is supplied through a series of workshops. These workshops have included one day management overviews, 3- to 5-day intensive training sessions, and on-site assistance.

The HSPF code has not been static since its initial release. Major enhancements have been made to the sediment transport and general quality sections of the RCHRES code for Version 7 released in June 1981. HSPF's modular structure made these updates, as well as the debugging and error correction discussed above, relatively easy.

APPLICATIONS

Clinton River Basin

The Macomb County, Michigan (north of Detroit), Public Works Department used HSPF to evaluate stormwater management alternatives for small study areas within the Clinton River Basin (Winn and Barnes, 1982). The model was first calibrated for the entire basin and then 48 years of streamflow were simulated using historical rainfall records and present land use. This was done to generate a consistently long record of streamflow for the basin under present land use to select a representative flood event for further study. The year of the largest simulated flood was then selected to evaluate a number of alternatives on a small 1,942 hectare watershed within the basin. Drainage within the watershed, which is 32 percent urbanized, is provided by nine county drains. In addition, five borrow pits and seven man-made lakes are available to store stormwater runoff. Future development in the watershed is expected to increase the severity of flooding problems.

Two flood events were simulated with HSPF -- the first with present land use and the second assuming full development in accordance with the Master Land Use and Zoning Plan. These floods were then routed through a combination of drainage facilities with and without retention. The combinations studied included the present drainage system, enlarged drainage channels, and enlarged channels with extra storage consisting of wide channel top-width and lake storage.

Results were analyzed for three combinations of land use and drainage configuration -- (1) present land use and drainage, (2) future land use with enlarged channels, and (3) future land use with enlarged channels having extra storage. Results showed that combination #2 had peak flows two to three times greater than present conditions (combination #1). The addition of wider channel tops and lake storage (combination #3) reduced peak floods to levels under present land use and drainage conditions (combination #1). The study concluded that it would not be sufficient to just enlarge existing channels; extra channel and lake storage would be required to contain major floods when the watershed is fully developed.

In this study, watershed simulation made possible the selection of an appropriate site-specific design event and the analysis of differing land use and drainage combinations. By allowing consideration of the watershed as a complete system, local site-specific costs could be traded off against the cost of downstream improvements, thus taking advantage of the economies of scale.

Little Seneca Creek Watershed

Schuelar and Sullivan (1983) describe an application of HSPF to the Little Seneca Creek watershed. The 5,180 hectare, mostly agricultural watershed is located 40 km northeast of Washington, DC, and is under intense pressure for urban development. A planned lake will serve as an emergency water supply reservoir and as a recreation resource. Local concern about the water quality impacts of urbanization prompted a comprehensive 3-year study of the watershed. Key concerns were the nature and magnitude of impacts to surface water quantity and quality, the effectiveness of nonpoint source and stormwater management controls in mitigating these impacts, and the investment required to maintain water quality.

The study was part of an evaluation of nonpoint source controls in the Washington area sponsored by EPA's National Urban Runoff Program. It included an intensive monitoring program, an application of the HSPF model, and an evaluation of planning alternatives and control and management practices. The land use planning alternatives considered included agricultural preservation, mixed low-density development with some preservation of agriculture, and wide-spread residential/commercial/industrial use.

HSPF was first calibrated and verified on the 26,160 hectare Seneca Creek watershed, of which Little Seneca Creek is a subwatershed. To account for differing hydrologic response, 5 land uses were simulated -- forest, row crops, pasture, and low- and high-density development. The calibration and verification data base consisted of 9 years of routinely collected quantity and quality data and 18 months of flow-integrated storm samples. Model results were compared to data for 6 water quality constituents -- sediment, total phosphorus, nitrate-N, organic-N, ammonia-N, and dissolved oxygen. Linear regressions of observed and simulated storm loads for 24 events produced correlation coefficients greater than 0.89 for all constituents. The authors characterized model performance as "very satisfactory."

HSPF was then used to project the nonpoint loads, erosion and water quality impacts of several alternatives using a "typical" year. Average annual runoff was projected to increase 22 to 39 percent over existing conditions and summer low flows to decline 10 to 20 percent. Stream bank erosion and sediment concentrations were projected to increase markedly because of higher water velocities, increasing stress on aquatic habitat. Phosphorus loads to the planned lake were not projected to be much higher than existing loads, with mean annual chlorophyll a increasing from 26 to 32 ug/l in the worst scenario.

After consideration of the water quality and habitat impacts of alternative development, the effectiveness of controls and management practices were examined. Options evaluated included agricultural management, stormwater management, urban nonpoint source controls, and combined agricultural/urban nonpoint controls. Agricultural controls consisted of conservation practices and grassed waterways for cropland and waste management for livestock operations. Dry ponds were simulated to replicate stormwater controls, controlling peak discharge but providing no reduction in nonpoint sources. Evaluation of urban nonpoint source controls considered wet ponds capable of maintaining the 2-year predevelopment peak discharge for low-density development and extended detention (drawdown time > 30 hours) wet ponds for high density development.

The analysis indicated that wet ponds out-performed dry ponds, controlling streambank erosion and reducing impacts on the lake. Agricultural controls protected the lake but did not protect the streams as well as wet ponds. Combined agricultural practices and wet ponds were capable of reducing phosphorus loads to the lake below existing conditions but were not able to prevent some increase in streambank erosion. Cost analyses indicated that agricultural controls achieved the most water quality benefit per dollar spent but did not protect stream habitat. Wet ponds were expensive but effective, with some economies of scale gained by an off-site pond program. Dry ponds offered only marginal water quality benefits.

These two applications of HSPF illustrate the usefulness of complete systems analysis in urban drainage planning. Both applications allowed the consideration of a wide range of planning and control alternatives, including an evaluation of on-site versus off-site control strategies. HSPF's flexibility, while sometimes making it difficult to use, is a key factor in its general utility.

THE FUTURE

One major problem users have encountered is setting up a comprehensive application. Thus, a user-friendly input editor is under development (Lumb and Kittle, 1984) and a preliminary version will be part of the next release. This editor will offer on-line assistance to users and interactively check their input for errors and validity. We anticipate no significant enhancements in the simulation algorithms in the immediate future. Rather, a period of applications and evaluation is expected. A new release will be made in mid-1984 (Johanson et al., 1984) that will consist mainly of error correction and minor enhancements to increase system utility. A program of continuing maintenance is planned over the next several years.

CONCLUSIONS

HSPF has been in use for more than 3 years. In that time, a number of applications have been completed and the program has rapidly matured. HSPF has become an accepted tool for use in a range of water quantity and quality assessments. It encompasses a wide range of simulation capabilities and is proven in a number of applications. The care and discipline practiced in the development of the program has paid off in a low frequency of errors and a relative ease of modification and enhancement. Although developed by EPA primarily for evaluation of agricultural problems, HSPF has also proven useful in urban drainage assessments.

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